CHAPTER 5

DESIGN OF VERTICAL WALL STRUCTURES

5-1. Sheet-Pile Structures. A sheet-pile structure consists of a line of piles engaged or interlocked to form a continuous wall. Piling is usually of steel, reinforced concrete, timber, or other materials. Choice of material will depend on relative cost, suitability for the intended use, and ability to resist lateral pressures. The cost of withdrawal and salvage value should be considered in the case of temporary works. For further design guidance, EM 1110-2-2906 should be consulted.

5-2. Steel Sheet Piles. Steel sheet piles are used for breakwater construction in three basic ways: (a) a single line of piling; (b) two parallel rows of piling connected by crosswalls or tie rods, and with sand or gravel fill between the walls; and (c) cellular units having either circular or semi-circular sidewalls and crosswalls filled with sand or gravel. The last two types of construction are usually capped with large stones, a concrete slab, or bituminous paving. Corrosion protection should be provided on all steel sheet-pile structures.

a. Single-Wall Sheet Piles. The single-wall type is either buttressed on the harbor side by short lines of piles driven perpendicular to the main line, as shown in figure 5-1, or the piling is reversed to give a deep section. On the straight-wall type, wales are placed near the pile tops. They may be channel irons or heavy timbers bolted to each pile. Since stability of the single-wall type of structure is dependent upon its strength as a cantilever beam, deep web sections should be used. The penetration necessary to develop the required amount of resistance to cantilever action is governed by the wave forces present and the type of bottom materials. The necessary depth of penetration varies considerably with type of material; thus, a careful study should be made of the bed material.

b. Double-Wall Sheet Piles.

(1) Where steel sheet piling is used in depths that impose forces beyond its strength to resist as a cantilever, an adequate system of bracing must be provided. This is usually accomplished by constructing two walls approximately as far apart as the depth of the water. Each wall is stiffened with wales and attached to the other wall with tie rods. Further support can be provided by crosswalls of the same material at appropriate distances, which divide the breakwater into a series of bottomless cells or boxes. For further stability, the boxes are filled with stone or sand and capped with concrete, asphalt, or large stones. A reinforced concrete or asphalt cap is preferable as a covering for sand since it prevents loss of material by wave overtopping. Inspection manholes should be provided in the cap at regular intervals so that additional fill material can be added whenever needed.

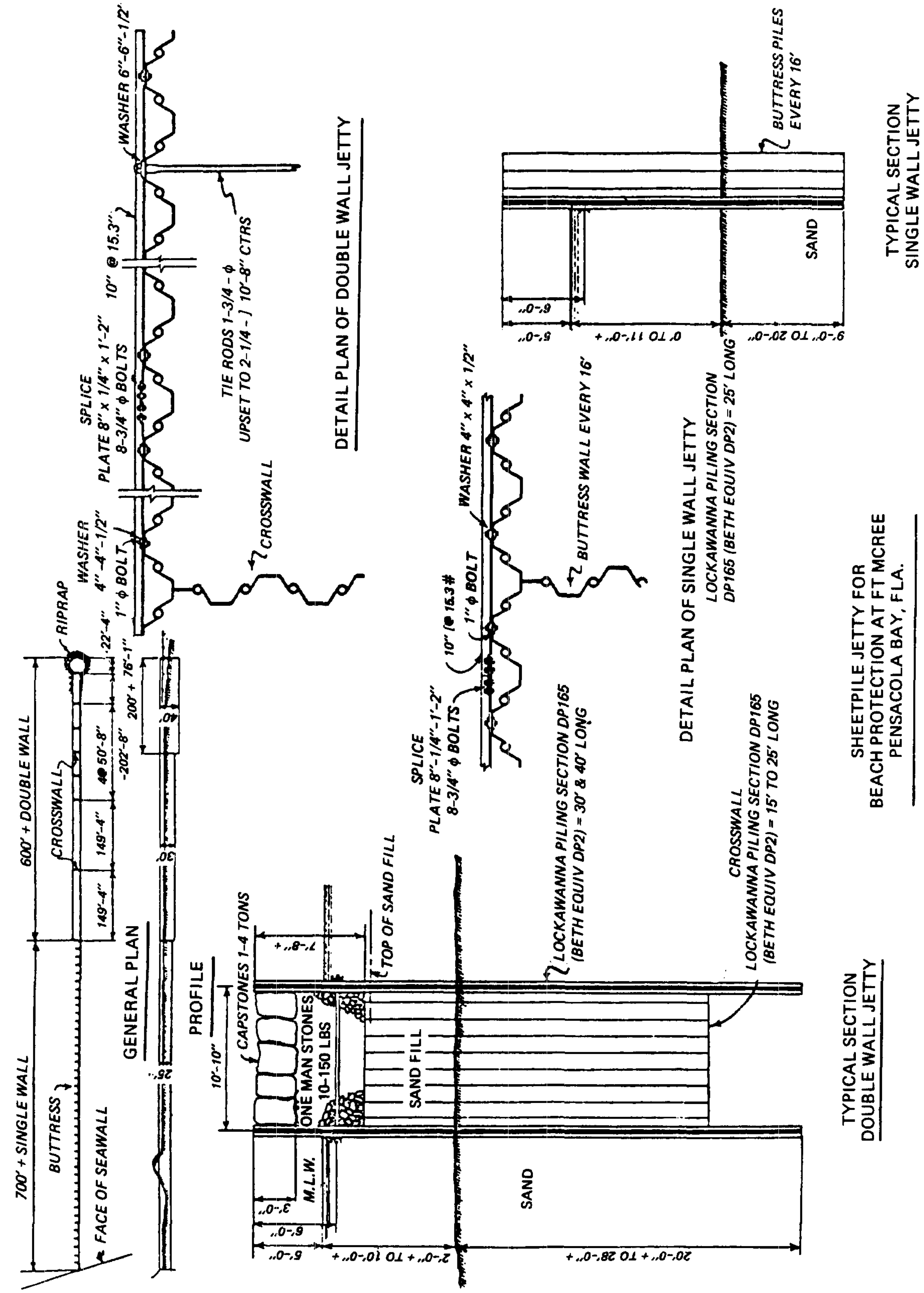


Figure 5-1. Typical steel sheet-pile jetty

(2) Experience has shown that the inside wales are preferable to outside wales; placing the wales inside protects them from the wave action and impact loadings from floating ice or other debris. Wales or other fixtures that tend to hold moisture and corrode should be located above high tide or below low tide.

c. Cellular Sheet Piles.

(1) When the breakwater is to be constructed in deep water, the use of underwater tie rods and wales becomes important: any system which requires the extensive use of divers is likely to be prohibitive in cost. To avoid this problem and to provide greater stability, cellular-type structures can be considered.

(2) Two types of cellular structures are currently used. The diaphragm-type, illustrated in figure 5-2, consists of a series of arcs connected to cross-diaphragm walls by means of fabricated Y-pieces. The legs of the Y-pieces form three 120-degree angles, making the tension in the cross-walls and arcs equal. The average width of the diaphragm type shown is 0.9 of the outside width.

(3) The circular type of breakwater, shown in figure 5-3, consists of a series of complete circles connected by shorter arcs, which are joined to the circles by means of fabricated T-pieces. As the T-pieces are usually manufactured at a 90-degree angle, it is imperative that the two sets of circles be orthogonal; the distances and radii indicated in figure 5-3 give right-angle intersections of the circles. The average width of the circular type shown is 1.7 times the radius of the circular arc.

5-3. Timber Sheet Pile.

a. Timber sheet piling is used for breakwater or jetty construction in areas subject to only moderate wave action and in relatively shallow depths. For saltwater use, timber must be pressure-treated as protection against marine borers. Physical properties of the various kinds of woods suitable for structural purposes are described in timber engineering textbooks. The design of timber sheet cantilever walls follows the same procedures as for other materials.

b. The most common type of timber sheet piling is known as Wakefield piling, shown as Type C in figure 5-4. This type, which is usually made on the job, consists of three thicknesses of plank with the middle plank offset to form a tongue and groove. The tongue-and-groove shape is sometimes made from a single timber. However, considering the size of timber necessary, waste involved, and added expense of milling the tongue-and-groove, this type is considerably more expensive than the Wakefield pile. In addition, tongue-and-groove piling is more susceptible to twisting and warping. Where a watertight fit between piles is of secondary importance, a plain rectangular pile is quite often used.

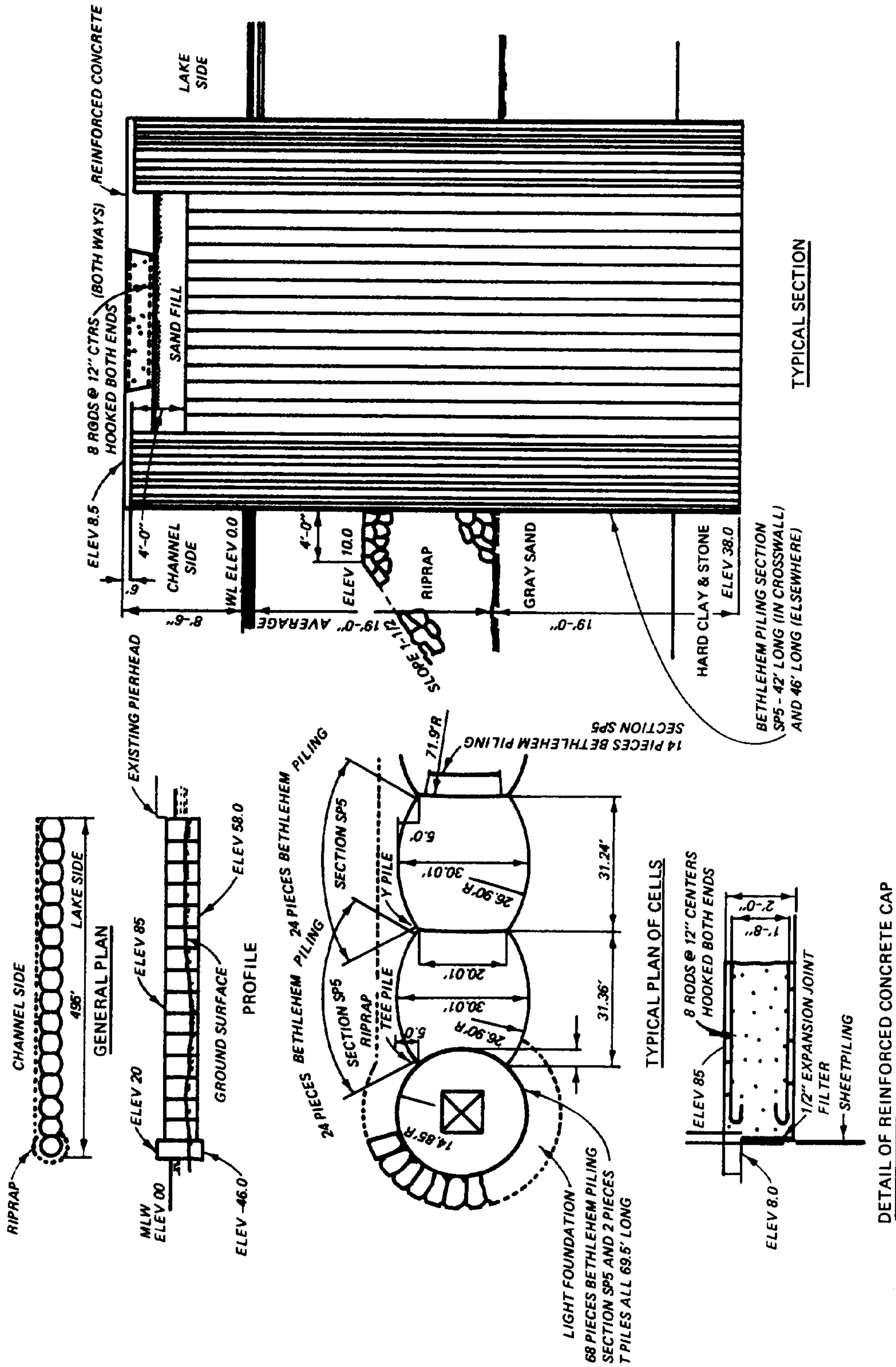


Figure 5-2. Diaphram type of cellular breakwater

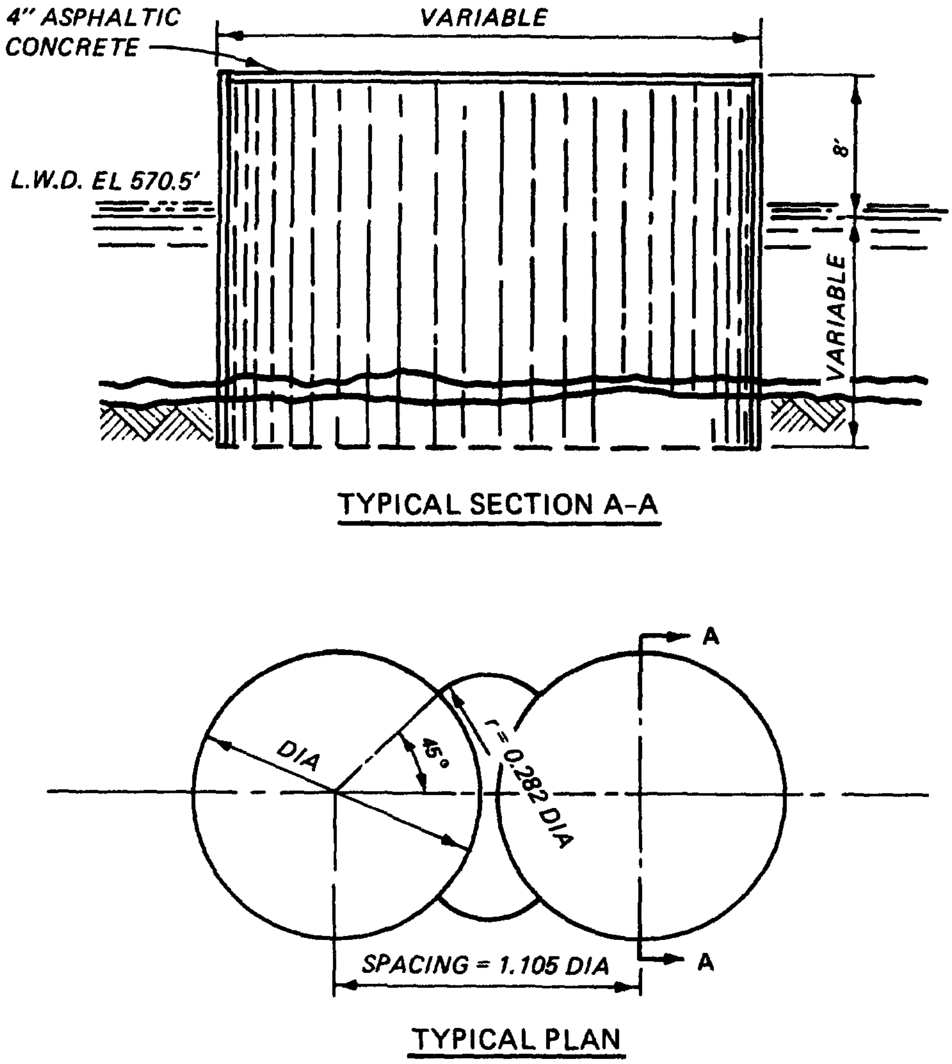


Figure 5-3. Circular type of cellular breakwater

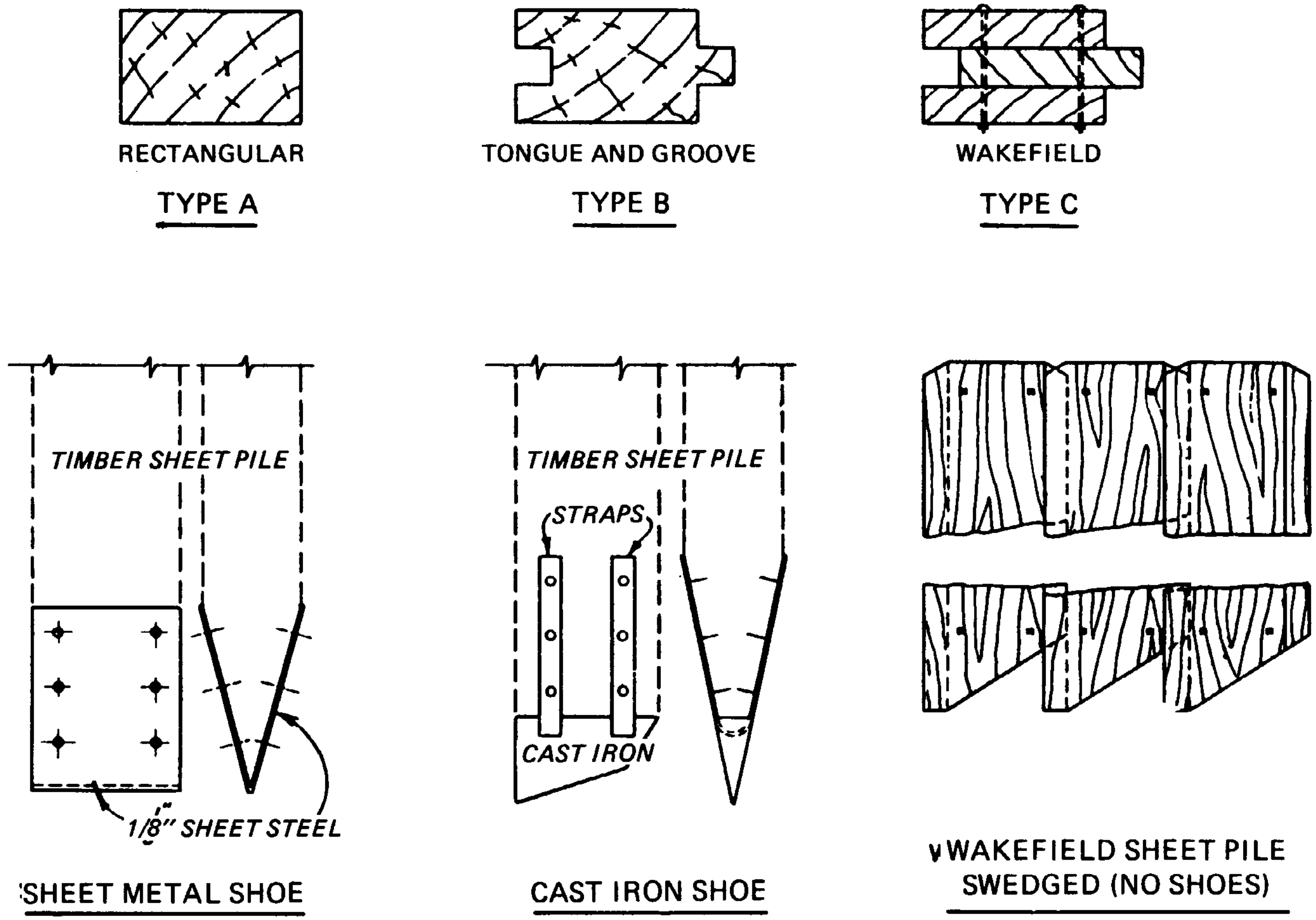


Figure 5-4. Typical timber sheet pile sections

5-4. Reinforced Concrete Piling.

a. If the forces which must be resisted have already been determined, pile dimensions, sizes, and spacing of the reinforcing bars are determined through application of ordinary reinforced concrete design principles. Depending upon the driving conditions, sheet metal or cast iron shoes can be fitted during the pouring operations. In order to ensure against corrosion, care should be taken in detailing the rebar so that an imbedment depth of at least 2 inches is obtained.

b. Typical sections of reinforced concrete piles are shown in figure 5-5. Special consideration should be given to the concrete composition when the structure is placed in saltwater, water contaminated by strong industrial residues, or in regions subjected to severe ice conditions.

c. Depending upon the type of structure desired, concrete pile forms can be constructed to obtain almost any type of shape of compression interlocking. Tension interlocks consisting of cast-in-place metal strips should be avoided because of concrete's low tensile strength. However, piles of this nature have been used as crosswalls between parallel rows of piles. The fill material between the outer rows causes the crosswalls to be in tension. Where the individual piles are securely held in position either by wales or a cast-in-place top covering, a satisfactory degree of water-tightness can be obtained by grouting between specially designed interlocks.

d. Concrete sheet piling should be specified using Guide Specification CEGS 02366, Precast Concrete Piling, or CEGS 02362, Prestressed Concrete Piling, as applicable. The concrete should be resistant to abrasion and not subject to disintegration when exposed to air, seawater, or freezing and thawing.

5-5. Wave Force Computations.

a. Wave forces exerted on vertical wall structures can be distinguished as being due to either nonbreaking, breaking, or broken waves. Whether a structure is subject to a single wave type or a combination of wave types depends on the wave climate, water depth, foreshore slope, and structure geometry.

b. The force due to nonbreaking waves is essentially hydrostatic. Sainflou's method or the modified Sainflou method, also referred to as the Miche-Rundgren method (item 132), is generally considered adequate for the vertical wall case. Figure 5-6 shows the wave pressure distribution according to the Sainflou method. ABED is the pressure diagram of the surface pressure due to wave action, DEC is the still-water pressure diagram, P is the value of the pressure due to wave action at the seabed, and h_o is the rise of the mean level of the clapotis (standing wave) formed due to the reflecting wave. Sainflou's equation for peak pressure involves hyperbolic trigonometric functions. The Miche-Rundgren method approximates the pressure distribution by a straight line as shown in figure 5-6. In this case, the only quantities

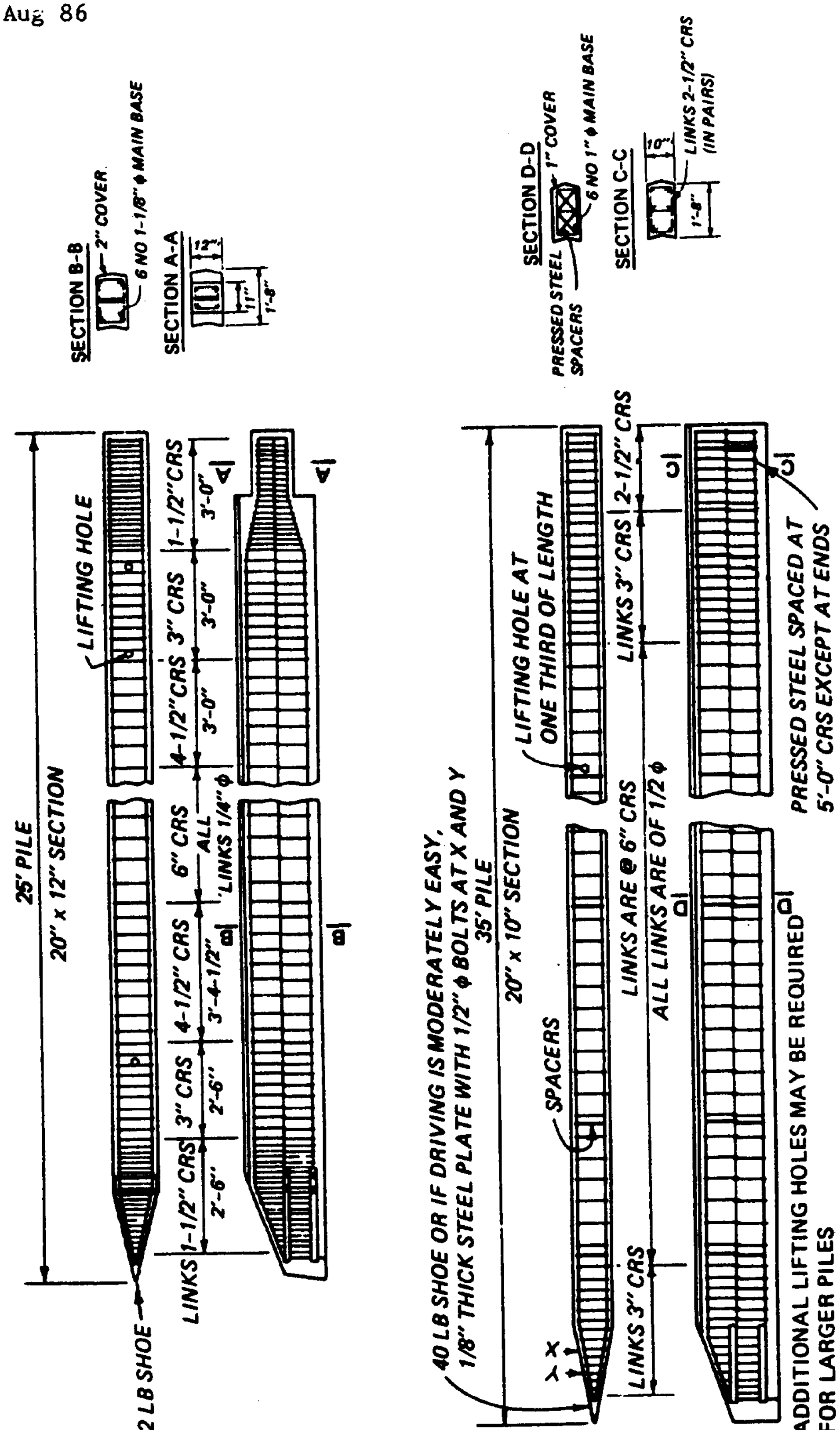


Figure 5.5 Typical reinforced concrete sheet pile sections

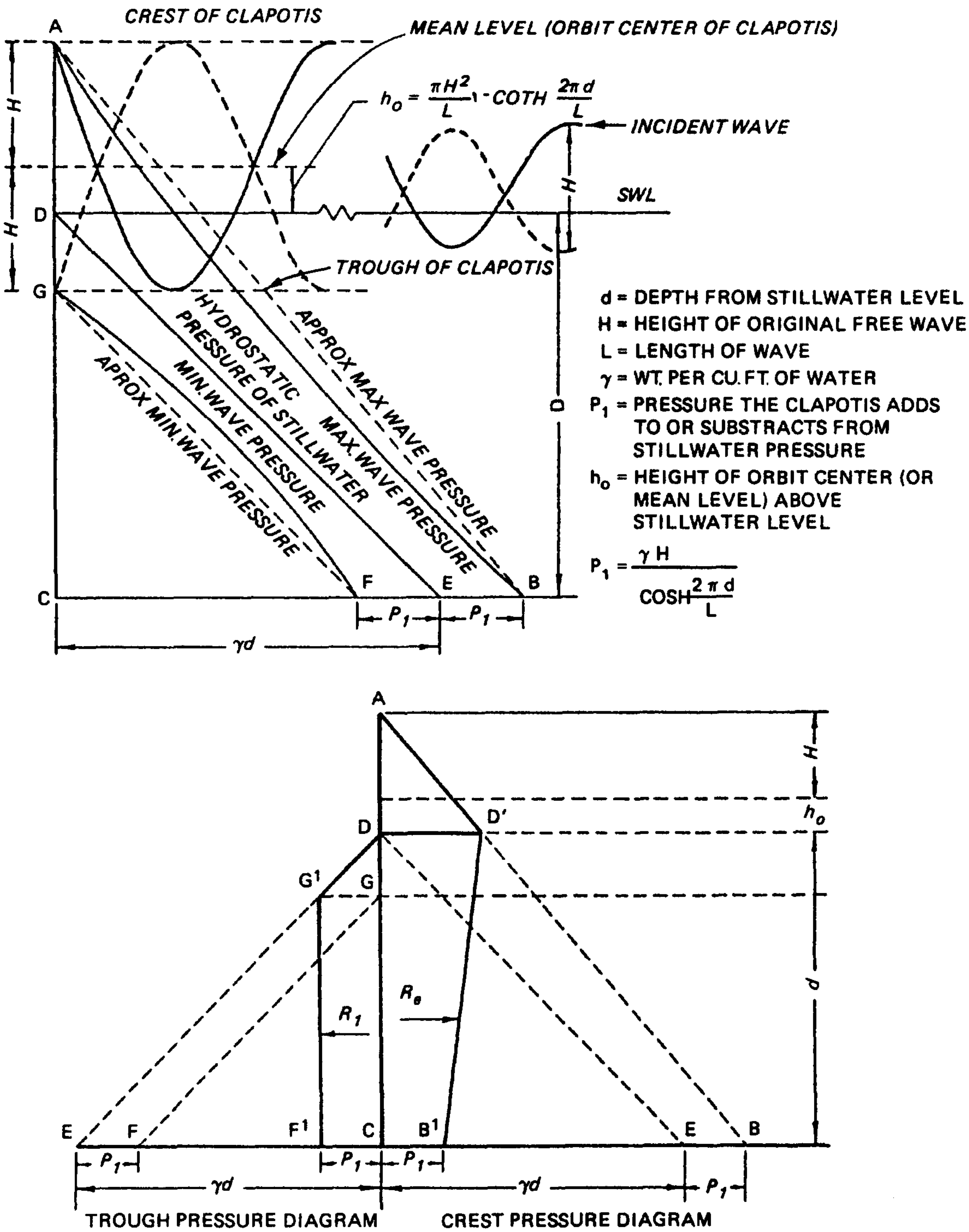


Figure 5-6. Nonbreaking wave loading on a vertical wall

which must be evaluated before the diagram can be drawn are the values of P_1 and h_o. These values are:

$$P_1 = \frac{1 + x}{2} \left[\frac{\gamma H_i}{\cosh(2\pi d/L)} \right] \tag{5-1}$$

$$h_o = \frac{\pi H^2}{L} \coth \frac{2\pi d}{L} \tag{5-2}$$

where

x = wave reflection coefficient (1.0 for vertical wall)

γ = specific weight of seawater

H = wave height

L = wave length

d = water depth

The corresponding resultant forces (R) and moments about the base (M) are given, respectively, for the maximum crest level (subscript e) and the maximum trough level (subscript i) by the following equations:

$$R_e = \frac{(d + H + h_o)\ \gamma d + P_1)}{2} - \frac{\gamma d^2}{2} \tag{5-3}$$

$$M_e = \frac{(d + h_o + H)^2\ (\gamma d + P_1)}{6} - \frac{\gamma d^3}{6} \tag{5-4}$$

$$R_i = \frac{\gamma d^2}{2} - \frac{(d + h_o - H)\ (\gamma d - P_1)}{2} \tag{5-5}$$

$$M_i = \frac{\gamma d^3}{2} - \frac{(d + h_o - H)^2\ (\gamma d - P_1)}{6} \tag{5-6}$$

c. Waves breaking directly against the structure face sometimes exert high, short-duration, dynamic pressure that acts near the region where the crests hit the structure. At present, Minikin's equation (item 132) is widely used in the United States; in Japan, Hiroi's equation is generally accepted. The Minikin equation gives a pressure distribution (shown in figure 5-7a) with peak pressure at or near the still-water level; Hiroi's equation, on the other hand, assumes a uniform pressure distribution (shown in figure 5-7b). Minikin's equation yields considerably higher peak pressure than Hiroi's, although the resulting total forces given by these two equations are similar for shallow-water cases. Both equations overestimate the total force and overturning moment when the water depth gets deeper. Items 54 and 99 present alternative equations for computing wave loading. Based on these works, the following equations are recommended:

(1) Peak impact pressure (P_m).

$$P_m = 2.5 \gamma H \text{ tons per square foot} \tag{5-7}$$

(2) Total force (F_t).

(a) If $H/L_o < 0.045$,

$$F_t = 3H + P_1 \text{ (Sainflou) tons per lineal foot} \tag{5-8}$$

(b) If $H/L_o > 0.045$,

$$F_t = 4H \text{ tons per lineal foot} \tag{5-9}$$

(3) Moment (M)

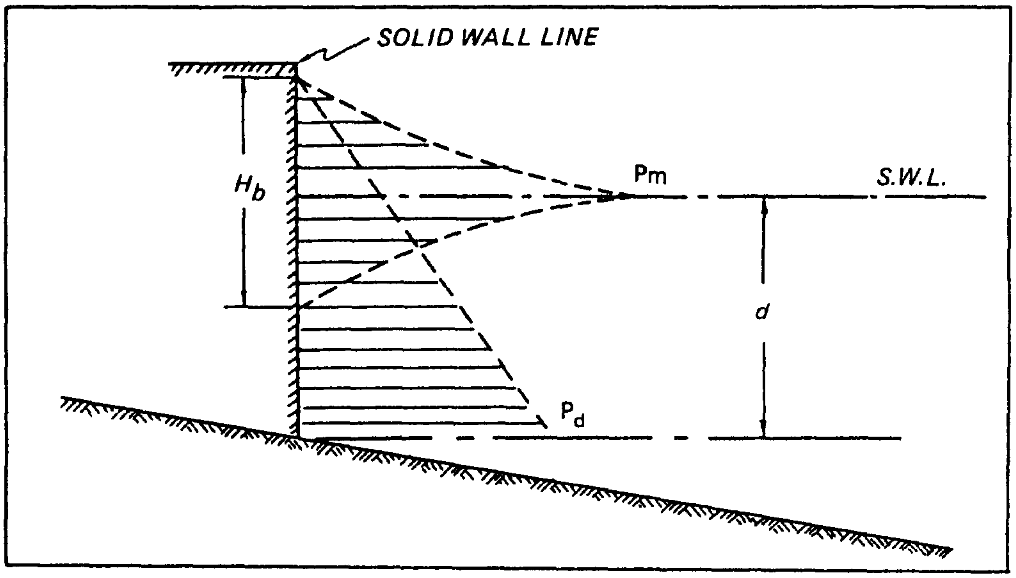
(a) If $H/L_o < 0.045$. (5-10)

$$M = 8H^2d \text{ ton-feet per lineal foot}$$

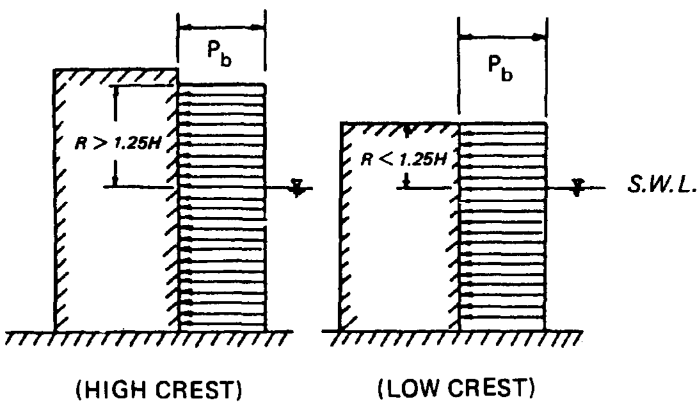
(b) If $H/L_o > 0.045$,

$$M = 12.5H^3 \text{ ton-feet per lineal foot} \tag{5-11}$$

5-6. Maintenance. Structures should be inspected on a periodic basis to identify maintenance needs. Timbers showing evidence of rot, decay, or marine borer intrusion can be replaced. Steel piling that is significantly weakened from corrosion may need to be replaced. Concrete structures should be inspected for cracking and sealed as needed to prevent intrusion of water.



a. Minikin Formula



b. Hiroi Formula

Figure 5-7. Breaking Wave Pressure Distribution on Vertical Walls

The overall stability of vertical wall structures is highly dependent on their toe stability; therefore, toe scour problems should be monitored and quickly corrected.

5-7. Rehabilitation. Structures that have sustained major damage from storms or have deteriorated to the extent that normal maintenance is impractical may require rehabilitation. If rehabilitation plans call for replacement of major structural features, the economic analysis should consider alternate types of structures, e.g., a timber structure might be most advantageously rehabilitated with steel sheet piling.